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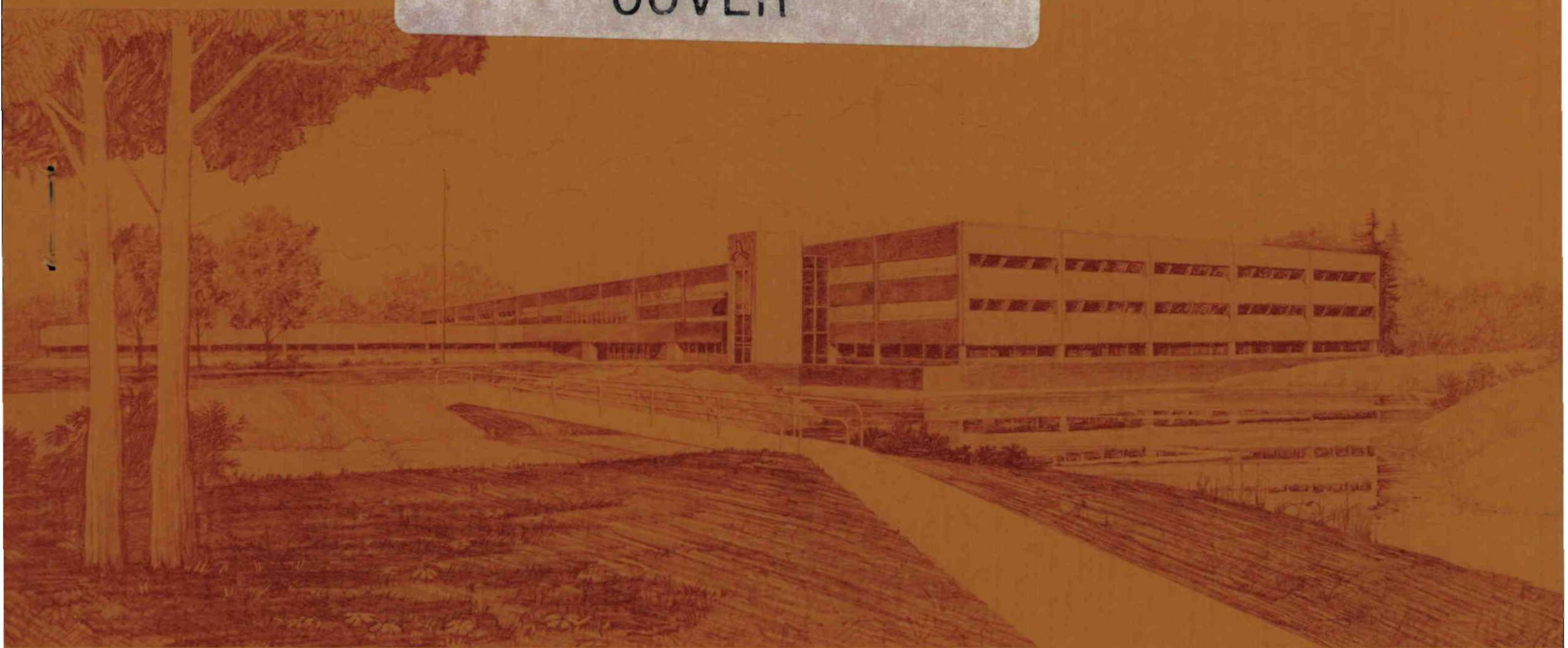

Idaho National Engineering Laboratory
Operated by the U.S. Department of Energy

Determination of the Availability of Core Exit Thermocouples During Severe Accident Situations

Jerald L. Edson

April 1985

Prepared for the
U.S. Nuclear Regulatory Commission
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DETERMINATION OF THE AVAILABILITY OF CORE EXIT THERMOCOUPLES DURING SEVERE ACCIDENT SITUATIONS

Jerald L. Edson

Published April 1985

EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

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ABSTRACT

This report presents the findings and recommendations of the Nuclear Power Plant Instrumentation Evaluation (NPPIE) program concerning signal validation methods to determine the on-line availability of core exit thermocouples during accident situations.

Methods of selecting appropriate signal validation techniques are discussed and sources of error identified. This report shows that through the use of these techniques the existence of high-temperature-caused errors may be detected as they occur.

Specific recommendations for application of selected signal validation techniques to core exit thermocouples and other measurement systems are made.

FIN No. A6369—Nuclear Power Plant Instrumentation Evaluation

SUMMARY

Core exit thermocouples in a nuclear reactor plant provide an indication of the state of the nuclear core during accident situations. However, these thermocouples have been shown to be subject to significant errors for installations where the thermocouple cable enters the vessel at the bottom and is routed through the core to the measuring junction. Errors due to this type of installation are not easily detected by observing only the indicated temperature and, therefore, on-line signal validation methods should be used to provide information concerning the validity of the data. This report addresses the errors that could exist and examines potential techniques for performing on-line signal validation. Appendix A contains a complete description of the various signal validation techniques considered. In addition, a thermocouple model that has proven useful in evaluating techniques utilizing ac excitation of the thermocouple circuit is presented in Appendix B.

Three techniques, judged to have the most likelihood of success, are investigated in detail. These techniques are: (a) noise analysis, (b) measurement of loop impedance, and (c) redundancy and statistical analysis. This report recommends a combination of impedance measurements along with range and statistical checks for on-line validation. In addition, it was concluded that these techniques are also suitable for other measurements that require signal validation.

Areas of concern for successful implementation of signal validation techniques are: (a) change in impedance with respect to total impedance, (b) predicted temperature profile within the core during a severe accident, and (c) predicted relationship of core exit thermocouples to each other during a severe accident.

ACKNOWLEDGMENTS

The author is grateful for the efforts and constructive comments provided by several individuals who have contributed to this report. M. O. Fryer and N. Wilde have contributed significantly with development of the thermocouple model and determination of electrical characteristics of the various materials that compose a thermocouple. L. D. Goodrich has been particularly helpful in the area of applying statistical and redundancy checks to on-line signal validation. S. B. Englert has worked long hours and has provided much needed advice and assistance in the laboratory tests that were performed in support of this effort. A. C. Williams has provided constructive review comments that have been very helpful.

ACRONYMS AND ABBREVIATIONS

ac	Alternating current
AWG	American Wire Gauge
CET	Core Exit Thermocouple
dB	Decibel
dc	Direct current
emf	Electromotive force
Hz	Hertz
ICC	Inadequate Core Cooling
LOFT	Loss of Fluid Test
L,R,C,	Inductance, Resistance, Capacitance
MHz	Megahertz
NBS	National Bureau of Standards
NRC	Nuclear Regulatory Commission
PAR	Princeton Applied Research
PWR	Pressurized Water Reactor
RMS	Root mean square
RTD	Resistance Temperature Detector
SCR	Silicon Controlled Rectifiers
SPND	Self Powered Neutron Detectors
TC	Thermocouple
TDR	Time Domain Reflectometry

CONTENTS

FIGURES

TABLES

DETERMINATION OF THE AVAILABILITY OF CORE EXIT THERMOCOUPLES DURING SEVERE ACCIDENT SITUATIONS

INTRODUCTION

Some commercial light water nuclear reactors have installed core exit thermocouples (CET) that may experience significant errors during accident conditions due to electrical shunting caused by decreased insulation resistance when the reactor core is experiencing high temperature. Information from core exit thermocouples should be used by operating crews in making decisions concerning both the status of the plant and appropriate actions to control an accident. Therefore, the core exit thermocouple readings should be a valid indication of core exit temperature. In addition, NUREG 0737,[1] Section II.F.2, (Clarification of TMI Action Plan Requirements) requires instrumentation for the detection of inadequate core cooling (ICC) which is unambiguous and which has the capability to determine the operational availability of each monitoring channel during reactor operation. On-line signal validation is a way of indicating when the signals from the core exit thermocouples may be reliably used.

High temperature caused errors are frequently of the type that begin small and become large as temperature increases. This type of behavior is very difficult to detect since there are no sudden, noncontinuous responses to alert the operating crew that a problem is developing. In fact, errors can be difficult, if not nearly impossible, to visually separate from legitimate signals during periods of high temperature. On-line signal validation then becomes the only reliable way to detect and display the existence of these errors. Therefore, this report concentrates on signal validation techniques that have the ability to continuously monitor the output and/or physical characteristics of the thermocouples and detect a departure from acceptable conditions.

This report presents the results of an investigation into potential methods of performing on-line determinations of the availability (or signal validation) of core exit thermocouples during accident situations. A logical process is developed and presented for defining what is required of a signal validation technique and how to select potentially successful techniques for further investigation. Secondly, a thermocouple (TC) model is presented that includes alternating current (ac) elements as well as direct current (dc) elements. This model facilitates the investigation of signal validation techniques that employ ac excitations. Finally, the results of a detailed investigation into three different signal validation techniques are presented and discussed.

DESCRIPTION OF A CORE EXIT THERMOCOUPLE ASSEMBLY

Core exit thermocouples in a pressurized water reactor (PWR) enter the reactor vessel either through the top head and terminate several inches above the reactor core, or enter the reactor vessel through the bottom, are routed up through the core, and are terminated 15 to 20 cm (6 to 8 in.) above the core. Installations in which the thermocouples enter the bottom of the reactor vessel are much more likely to experience high temperature errors and will be described in some detail.

Core exit thermocouples that enter the bottom of the reactor vessel typically consist of a 1.59 mm (0.0625 in.) o.d. Inconel sheath, with aluminum oxide insulation, and 0.25 mm (0.010 in.) o.d. type K (chromel-alumel) wires. An undimensioned cross section of a typical TC is shown in Figure 1. A thermocouple circuit will consist of about 106.7 m (350 ft) of 2 conductor stranded 20 AWG shielded type K extension cable connected to about 39.6 m (130 ft) of metal sheathed thermocouple cable, as previously described, and terminated with a grounded thermocouple junction as shown in Figure 2. The thermocouples enter the bottom of the vessel and are routed up through the reactor core in instrument tubes as shown in Figure 3. Figure 4 shows a cross section of the instrument tube assembly. The incore instrument assembly consists of an Inconel sheath, seven self-powered neutron detectors (SPNDs), one background detector, and a spacer tube. This assembly is contained in an instrument tube and instrument sleeve. During normal operations there will be water between the sleeve and tube, and between the tube and instrument assembly. There are about 52 incore instrument assemblies in a nuclear core.

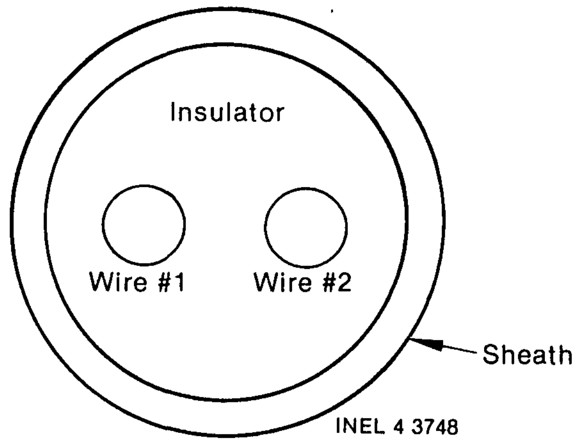

Figure 1. Cross-section of thermocouple.

Since high temperature related errors are primarily caused by high temperatures in the reactor core, only the portion of the thermocouple circuit from the bottom of the core to the measuring junction will be analyzed in the remainder of this report. However, it must be recognized that when implementing a signal validation technique the total circuit must be considered and included in any analysis.

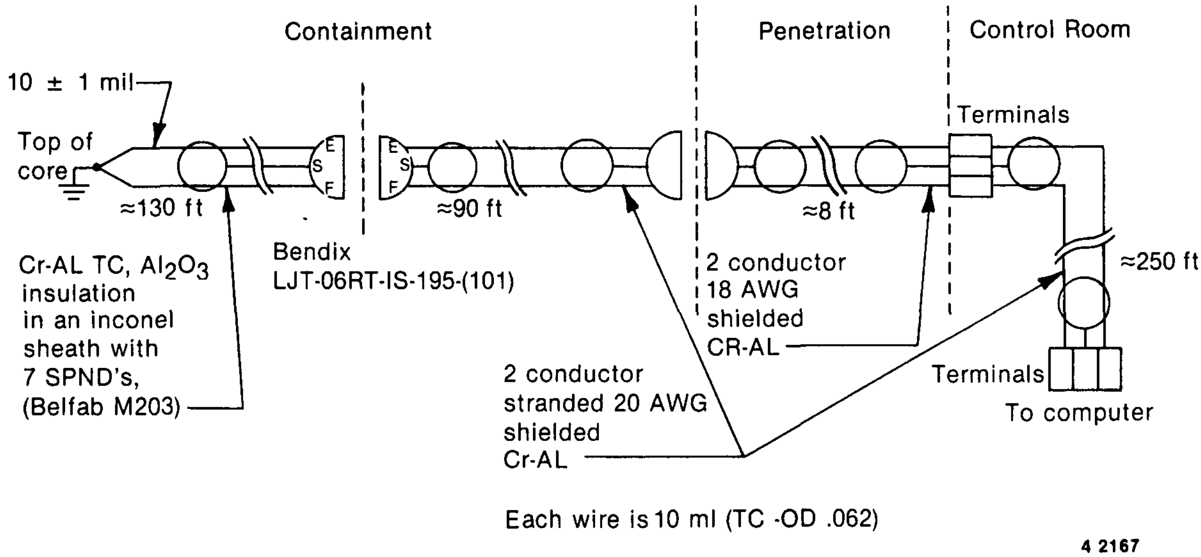

Figure 2. Typical thermocouple circuit.

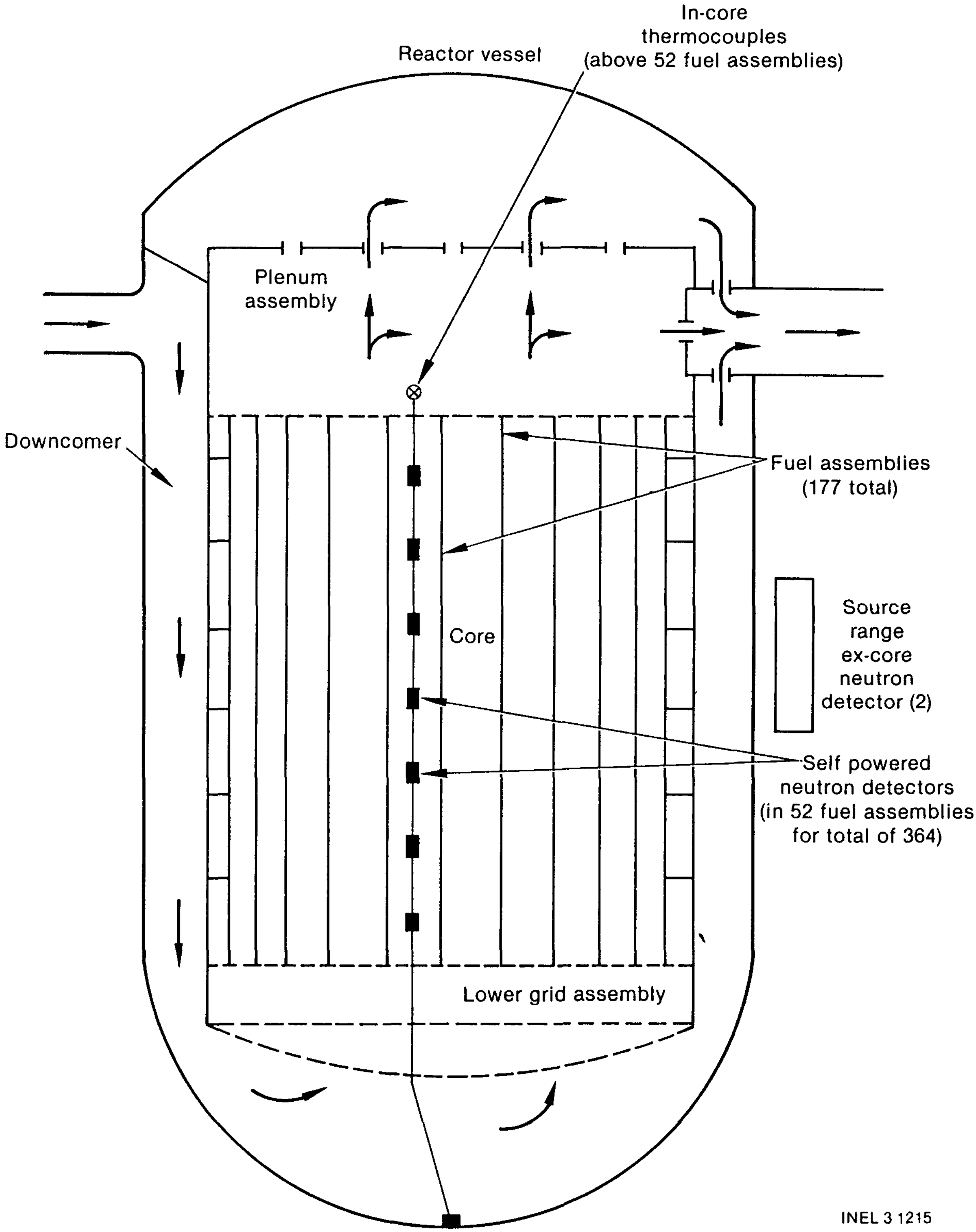

Figure 3. Reactor configuration and instrument locations.

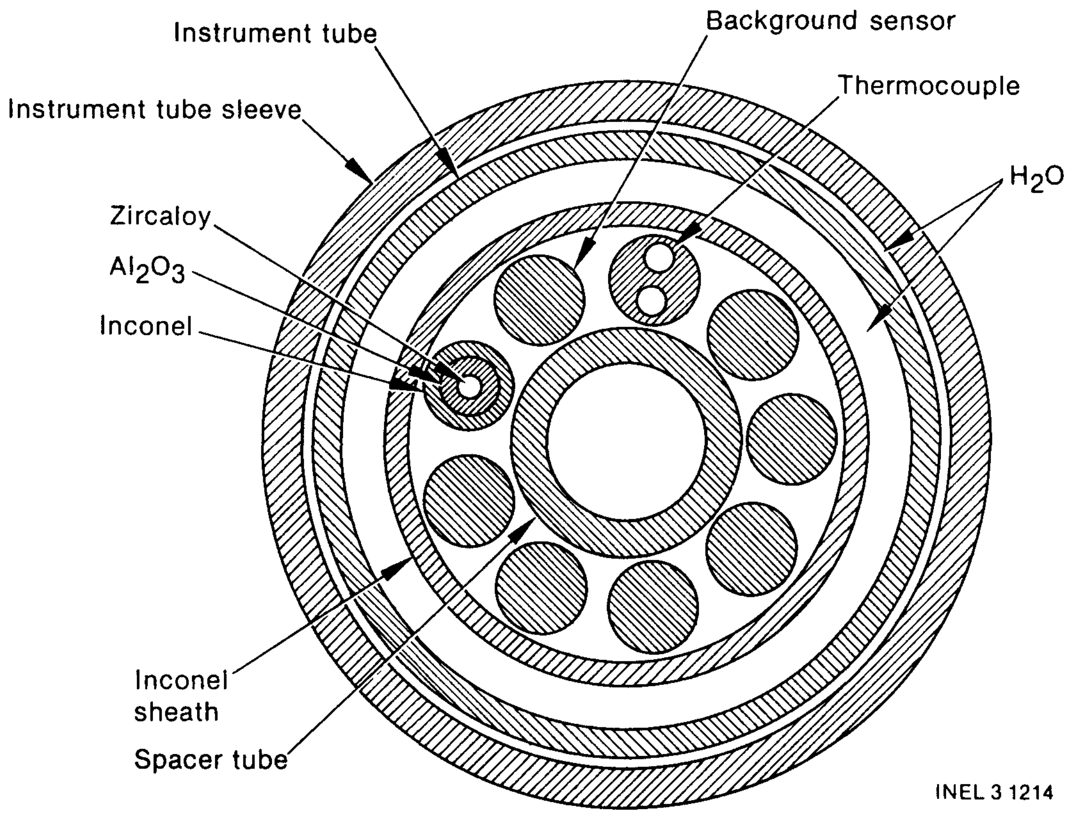

Figure 4. Instrument tube assembly cross-section.

SELECTION OF SIGNAL VALIDATION TECHNIQUES

A logical process was designed to identify those validation techniques that showed most promise for practical success. The process included the following steps:

- Identification of sources of thermocouple measurement system errors
- Evaluation and quantification of errors to identify those that are most significant to core exit thermocouples
- Specification of requirements that must be met by signal validation techniques
- Identification of possible signal validation techniques
- Choosing those techniques that appeared to have the most likelihood of successful application to an operating nuclear plant.

In the following section each step of the logical selection process will be discussed.

Identification of Sources of Errors

A thermocouple measurement system error is considered to have occurred whenever the recorded or displayed signal deviates from the National Bureau of Standards (NBS) standard curve[2] for the specified thermocouple. While a single document has not been found that is a complete listing of thermocouple system errors, a search of the literature[3-11] has produced a large list. Particularly useful is a discussion of error sources by A. C. Williams and Ned Wilde and reported in EGG-ED-6361.[3] The sources of errors produced by the literature search have been divided into four categories and are shown in Table 1.

Table 1. Thermocouple measurement system errors

Circuit Problems	EMF Problems	Recording/Display Errors	Thermocouple Response Errors
Open circuit	Seebeck coefficient changes	Aliasing	Size
Shorts	- Change in metallurgical/physical state	Response	Shape
		System uncertainty	Orientation
			Heat transfer properties
Shunting	Work hardening, annealing	Readability	
Changes in reactance	Recrystallization		
	Solution/precipitation of Constituents		
- Dielectric constant changes	Ordering effects		
	Dislocations caused by radiation		
	- Composition changes		
	Variations in Alloys		
	Impurities		
	Chemical Reactions		
	Selective Evaporation		
	Nuclear Transmutation		
	- Physical Forces		
	Elastic Strain		
	Static Pressure		
	Magnetic Flux		
	Unwanted EMFs		
	- Noise		
	- Chemically generated EMFs		
	- Electromechanical EMFs		
	- Thermo relaxation currents		
	- Extraneous EMFs		

These sources are:

- Those related to circuit problems.
- Those related to the generation of emfs.
- Those related to the response of the thermocouple to the physical phenomenon.
- Those related to recording and/or display of the thermocouple output.

Circuit problems are those that come about as a result of adverse changes in the circuit elements. These elements are primarily wire resistance, insulation resistance and reactance (capacitance and inductance). Variations in these elements can cause open circuits, short circuits, and shunting. Shunting is a condition that exists when the insulation resistance between the wires becomes low due to degradation of the insulation, or due to high temperatures that cause the insulation to have a low resistivity. Shunting, which should not be confused with mechanically caused short circuits, will be discussed in greater detail later in the report.

Emf problems are those that cause the output voltage to be in error either due to changes in the Seebeck Coefficient or due to the introduction of unwanted emfs such as noise. The Seebeck Coefficient is defined as: ". . . the rate of change of thermal emf with temperature at a given temperature, normally expressed as emf per unit temperature. Synonymous with thermoelectric power."[12] The Seebeck Coefficient describes the emf that is measured in an ideal thermocouple circuit. In addition, the Seebeck Coefficient is not a constant, but is a function of temperature and material properties. As can be seen from Table 1, the list of effects that can cause changes to the Seebeck Coefficient is long. However, work hardening and annealing, ordering effects, impurities, chemical reactions and nuclear transmutation are probably the most predominate.

A certain amount of heat energy must be transferred to or from the thermocouple for it to respond to a temperature change in the measured process. Since this heat transfer requires some time, there is a time delay between the indicated temperature and the actual temperature. This effect is known as response time or time constant. In addition, the thermocouple may be located some distance from the point in the system where temperature determination is needed. This causes a delay, not due to the response time of the thermocouple, but due to the time required for the system to respond to changes in temperature. Both types of delays cause measurement errors when temperature is changing.

All recording and display systems are sources of some error, however small, and contribute to the total measurement error of a thermocouple system. One of these error sources is aliasing, which is caused by sampling at a rate that is too slow for the rate of change in the signal. Other sources of error are response time of the recording or display system, uncertainty, and readability.

Evaluation and Quantification of Errors

Errors in each of the categories listed in Table 1 were evaluated to identify those that are most significant to core exit thermocouples. Significant errors that signal validation techniques should be able to detect were then identified.

Precise quantification of errors requires a knowledge of the immediate surrounding environment and also a knowledge of the history of the thermocouple system. Since these are not always well known, it is difficult to precisely predict the magnitude of the errors, particularly during accident situations. However, errors can be classified as being generally small or large, as has been done for this report. To reduce the number of variables that must be considered, quantification of errors was restricted to chromel-alumel (type K), aluminum oxide insulated, Inconel sheathed thermocouples. Core exit thermocouples are typically of this construction.

Recording and Display Errors. These errors are generally small and are not a function of accident conditions. For example, the uncertainties in the LOFT Data Acquisition System are 1.2% of range or less.[13] In addition, the recording and display portions of the measurement system are readily accessible during accident conditions and are therefore, much easier to check than the detectors. Therefore, on-line signal validation for recording and display errors is not considered to be of primary importance to this study.

Time Constant. The time constant of a 0.0625-in. o.d. thermocouple is <5 s in an air environment and even less in a water environment.[14] This time constant is short when compared to the events of an accident situation and the errors are not considered to be significant. Problems with the response of the core exit thermocouples to changes in core temperature have been documented in a report authored by J. P. Adams and G. E. McCreery, NUREG/CR-3386.[12] There is strong implication that the core exit thermocouples' indication of inadequate core cooling may be unreliable and ambiguous. It was concluded that any procedure that relies on the response of core exit thermocouples to monitor a core uncovery should take into account two limitations: 1) the time delay between core uncovery and the TC response, and 2) the difference between the temperature measured by the core exit TC and the maximum cladding temperatures in the core. It was further concluded that "There may be accident scenarios in which these TCs would not detect inadequate core cooling that preceded core damage."[15] However, since these errors are apparently thermal-hydraulic problems and not thermocouple performance problems, they are not considered to be within the scope of this report.

Emf Errors. A review of literature indicates that except for laboratory created situations, emf errors are not likely to be large but could be greater than the standard limits of error for a type K thermocouple ($\pm 2.2°C$ or 0.75% whichever is greater). R. L. Anderson, J. D. Lyons, T. G. Kollie, W. H. Christie, and R. Eby have reported[16] that "Thermoelectric inhomogeneties can be introduced in the thermoelements by physical changes, such as coldwork, by bending or stretching of the wires. The errors caused by such changes are usually $<10°C$ and can often be reduced or eliminated by annealing." They also reported that chemical reactions could cause large errors (hundreds of degrees). However, since core exit thermocouples have sheaths that protect the wires from the surroundings, these errors should not be significant. Long term drift and short term ordering in type K thermocouples with Inconel sheaths also cause relatively small errors ($<20°C$).[17] Type K thermocouples are not affected significantly by nuclear radiation ($<5°C$) as reported by P. Siltanen and T. Laaksonen of Finland and W. Joslin of Canada.[18] So, in conclusion, emf errors are expected to be small and are not considered to be significant for signal validation purposes.

Circuit Problems. Circuit problems generally relate to the overall health or operational availability of the measurement channel. While open and short circuit faults can cause large errors, it is usually obvious when they occur because the output changes quickly; the magnitude of the change is usually large and the final value of the output does not correspond to a logical temperature. There is one circuit related problem that can cause significant errors and yet may not be obvious, so that temperature indication might be ambiguous. This source of error is shunting caused by high temperature effects within the thermocouple cable. R. L. Anderson, L. A. Banda, and D. G. Cain have reported[19] that high temperature shunting errors can be significant during accident conditions, reaching several hundreds of degrees Centigrade. The magnitude of this error is dependent upon the profile of the high temperature zone with location, length and magnitude of the peak temperature being the most dominate factors for a specific thermocouple. The large shunting errors occur when the hottest part of the thermocouple cable is not located at the measuring junction but rather along the cable between the measuring junction and the reference junction. This is precisely the type of problem that could occur in nuclear reactors when the core exit thermocouple cables enter the reactor vessel at the bottom, are routed up through the nuclear core, and are then terminated with the measuring junction located above the core. When the hottest part of the cable is at the measuring junction, small errors ($<10°C$) occur. This would be typical of installations where the core exit thermocouples enter the reactor vessel at the top head.

Not only can shunting errors be large, but they do not occur instantly; nor do they occur as a result of an instant change in the system. Standard recording equipment will not detect the onset or existence of shunting errors. Instead, these errors progressively get larger as increasing temperature causes increased wire resistance and decreased insulation resistance. In addition, the temperature that controls shunting error (i.e., the hot spot on the thermocouple cable) is not usually measured or known. Therefore, high temperature caused shunting errors are nearly impossible to calculate as they occur.

Since circuit problems can realistically be significant during accident conditions and may not be readily obvious, they are considered to be important factors to the selection of signal validation techniques. As mentioned earlier, emf problems, response problems, and recording or display problems are not primary factors for signal validation of core exit thermocouples. However, it should be recognized that an ideal signal validation technique would detect the existence of all errors, regardless of the source, but probably does not exist for any given measurement system.

Specification of Requirements

Requirements for (a) choosing signal validation techniques to investigate, and (b) judging the ability of a technique to satisfactorily provide signal validation for core exit thermocouples, were established. The requirements were established based on what is to be detected, the expected use of the signal validation techniques, and consideration of the personnel that would be expected to implement and use them.

Requirements were divided into two categories called "mandatory" and "optional." "Mandatory" requirements are those that must be met while "optional" requirements are desired but not absolutely necessary. Establishing optional requirements was useful since it provided a basis for judging between techniques that were believed to provide all the mandatory requirements.

The following requirements were established:

Mandatory

- Must provide an indication of whether the signal is valid or invalid after recovery from the accident (the post accident phase).
- Must indicate the existence of an ambiguity in the signal caused by high temperature shunting during all phases of the accident.
- Must provide an unambiguous indication and must be reliable.
- Must be simple to use and interpret.
- Must utilize existing plant instrumentation. Requiring the installation of an additional instrument circuit is not acceptable.

Optional (Listed in descending order of importance)

- Provide a continuous display of the results of the signal validation. This requirement is nearly mandatory.
- Accomplish signal validation with a single display and a single method.

- Indicate the existence of any functional problem at any time.
- Identify the type/cause of the problem.
- Indicate the actual response time of the TC.
- Be qualifiable to class 1E standards.

Identification and Evaluation of Possible Signal Validation Techniques

The next step in the process was to list and evaluate potential signal validation techniques that appeared to be satisfactory. This was done based on INEL expert opinion in the areas of signal validation, diagnostics, measurements and thermocouples. A list of 18 candidate signal validation techniques applicable to core exit thermocouples was obtained. The process of obtaining the list did not include making a judgment of the "goodness" of any technique. That step was reserved until the list was compiled and evaluated. The evaluation consisted of determining each technique's likelihood of success and its relative cost. These evaluations were divided into three categories (high, medium, and low) and are relative in nature rather than absolute. The list is shown in Table 2. Each of the listed techniques are discussed in Appendix A.

Choosing Techniques for Further Investigation

The items of Table 2 were reviewed to determine those that appeared to have the highest likelihood of successful application to an operating nuclear plant. Those items with a relative cost of medium or low, a likelihood for success of medium or high, and which were applicable to accident conditions, were chosen for further consideration. Based on these criteria, three areas were chosen:

- Noise analysis, including both time domain and frequency domain analysis
- Measurement of loop impedance
- Comparison to other measurements. This technique also involves the use of some statistical methods and will be referred to as "Statistical and Redundancy Analysis" in subsequent sections of this report.

These techniques will be discussed in much greater detail in subsequent sections of the report. The discussions will include the results of investigations into the techniques to determine whether, in fact, they have applicability to a nuclear plant during accident conditions.

Table 2. Potential methods to determine operational availability of core exit thermocouples

Diagnostic Method	Likelihood for Success	Cost to Develop
1. Time Domain Noise Analysis[a]	M	L
2. Frequency Domain Noise Analysis[a]	M	M
3. Time Domain Reflectometry (TDR)	L	H
4. Response to Excitation	M	H
5. Measure Loop Impedance Measure Dielectric Constant Measure Insulation Impedance Measure Circuit Time Constant	M	M
6. Comparison to other TCs[a] Comparison to Other Measurements	M (M-H if combined with 5)	M
7. Compare to Past Data (Pre/Post Accident)	H	L
8. Use TC Wire as Tuned Legs of an Oscillator	L	H
9. Use TC Wires as Ultrasonic Conductors	L	H
10. Response to energy Input-Thermal Time Constant (Pre/Post Accident)	H	M
11. Utilize Peltier Effect	L	H
12. Excite one Conductor/Sheath-Signal Propagated in Other Conductor	L	H
13. Redesign TCs to be easier to test[b]		
14. Movable TCs[b]		
15. Redesign TC Routing[b]		
16. Locate TCs at the Hot Spot[b]		
17. Redesign TCs to Withstand Higher Temperature[b]		
18. Install Unjunctioned TCs[b]		

a. This method was selected for further investigation.

b. This method was not given further consideration as it required redesign or new instruments.

INVESTIGATION OF POTENTIAL SIGNAL VALIDATION TECHNIQUES

Preliminary Investigation

An initial evaluation was made of how to proceed with investigating the three different techniques: noise analysis, impedance measurement, and statistical and redundancy analysis. One fact that became apparent was that experimental data or some other data, such as analytically obtained data, would be needed to demonstrate the validity of the proposed signal validation techniques. In addition, it was recognized that it would be costly and time consuming to provide experimentally obtained data for the several different temperature profiles that are needed in order to show applicability to accident situations. This was particularly true for the impedance measurements; the use of alternating current excitation at many different frequencies would need to be investigated for each temperature profile. For this reason, it was decided that a model of the thermocouples would be employed as a tool, permitting economical investigation of impedance at many different frequencies and several different temperature profiles.

A literature search showed that while some TC models have been developed that do a good job of predicting dc thermocouple performance, they all are composed of direct current (dc) elements such as resistance, conductance, and voltage; they do not include the alternating current (ac) elements such as inductance, capacitance, and the frequency dependence of resistance. An example of an excellent model is one developed by M. J. Roberts and T. G. Kollie of ORNL.[20] This model has been successfully used and validated but is restricted to dc elements. Therefore, it became obvious that a thermocouple composed of both dc and ac elements should be developed to support the investigations of potential signal validation techniques.

The thermocouple model that was developed is composed of small sections containing both dc and ac circuit elements. Figure 1 shows a cross section of a sheathed thermocouple and Figure 5 shows a short section of an equivalent circuit of a sheathed thermocouple. This short section is composed of the elements of a three wire transmission line. The model, then, is composed of a series of short sections that describe the thermocouple. The size of these sections should be small compared to the distance over which significant changes occur in the

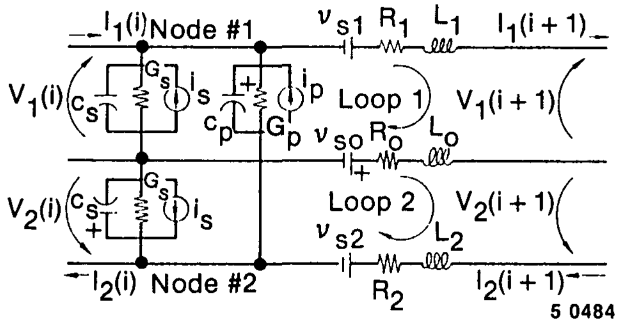

Figure 5. Equivalent circuit of thermocouple element.

TC parameters and the wave length of electromagnetic waves propagating in the TC. A more detailed description of the TC model is provided in Appendix B of this report.

The TC model has been implemented on the dual CYBER 176 system at the Idaho National Engineering Laboratory (INEL). As the model is currently written, up to 400 sections can be used to model the thermocouple. The model calculates the impedance of a TC using 400 sections in <1 s of CPU time and, therefore, is quite economical to use.

Model performance was determined by experimentally obtaining data from a section of heated thermocouple cable and comparing experimental results with calculated results. The data were obtained by heating a 3.66 m (12-ft) sample of TC cable in a Lindberg Horizontal Oven (Model 54253-N) that has a worst case accuracy of ±2°C. The impedance measurements were made with a Hewlett Packard (Model 419A) impedance meter having a worst case accuracy of ±2.5% of reading. The model predictions are shown in Figure 6 and the measured values are shown in Figure 7. The model predictions and the measurements are in good agreement. The most noticeable difference is that the experimental measurements showed a larger room temperature impedance at resonance. This difference is much less pronounced at higher temperature. In fact, the model and experimental data are in good agreement for most temperatures and frequencies. The average percentage difference between experimental and model results was 6.3%, with the worst case error being about 10% for temperatures between 300 and 900°C.

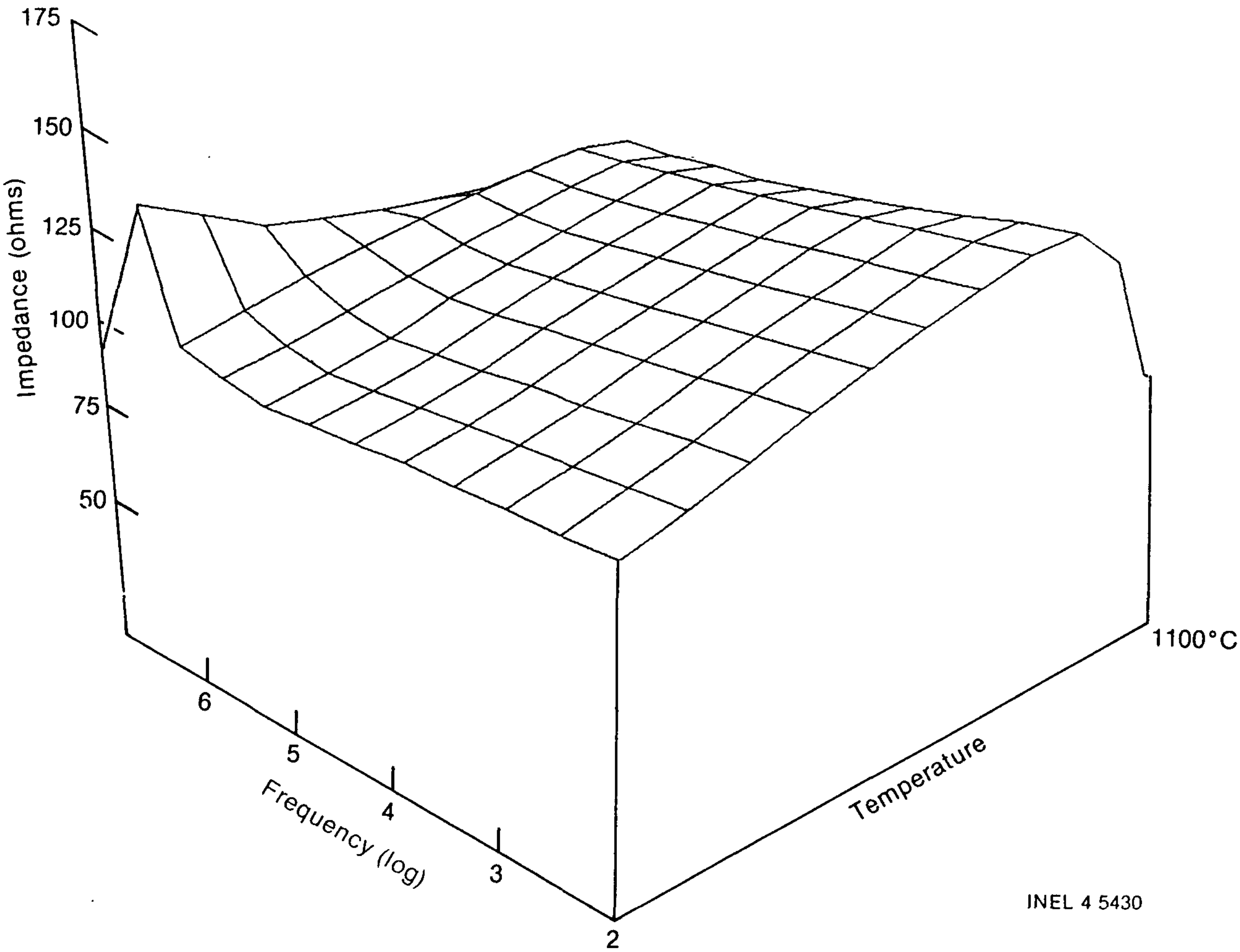

Figure 6. Model results for impedance.

Since model performance agreed well with experimentally obtained results, the model was used to investigate impedance characteristics of a thermocouple experiencing high temperature shunting effects. These investigations are presented in the section of this report on impedance measurements.

Detailed Investigation

Noise Analysis. It is known that a thermocouple circuit generates considerable noise when an open circuit failure is occurring, particularly if it is not a clean break. Additionally, some significant noise has been observed on LOFT cladding thermocouples during high temperature applications. Therefore, noise as a potential indicator of high temperature shunting was considered to be an option worth pursuing. Laboratory tests were conducted in which sections of thermocouple cables were heated to high temperatures and noise levels were measured. This section describes the tests that were conducted and the tests' results as they apply to determination of on-line availability of core exit thermocouples.

As stated previously, core exit thermocouples that enter the bottom of the reactor vessel and terminate with the hot or measuring junction located a few inches above the core are most susceptible to high temperature shunting effects. During a severe accident the high temperature region is not predicted to extend below the top half of the core until temperatures are high enough to melt the thermocouples. Since the objective of this task was to study techniques that would detect high temperature caused errors prior to melting of the thermocouples, it was not necessary to consider high temperature profiles that extended to the lower half of the core. Therefore, the temperature profile

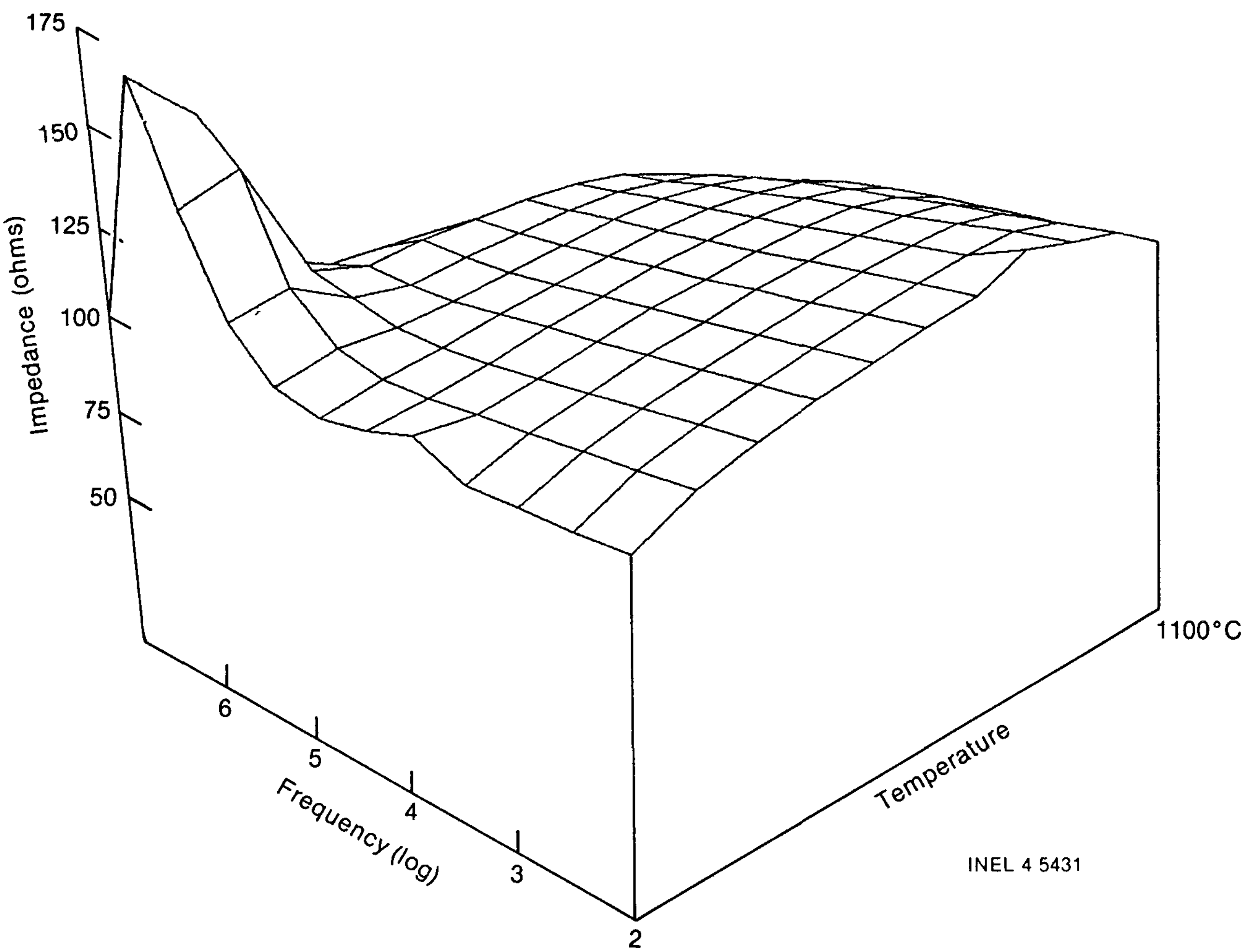

Figure 7. Experimental results for impedance.

shown in Figure 8 was utilized for laboratory tests since it was easy to achieve and included the range of the expected temperature profile of a severe accident. A maximum of 1271°C was selected as the peak temperature since it corresponds to the maximum usable temperature of a type K (chromel-alumel) thermocouple. The hot junction was immersed in a container of boiling water to maintain a known constant temperature. In addition this provided a large difference between the peak temperature and the measuring junction temperature. This is necessary in order to realize large high temperature shunting errors.

Three thermocouples were tested to provide both redundancy and variety. Two thermocouples, similar to core exit thermocouples in a commercial nuclear reactor, were constructed. These were aluminum oxide insulated, Inconel sheathed, type K, 1.59 mm (0.0625 in.) o.d. thermocouples. The third was manufactured by a different vendor and

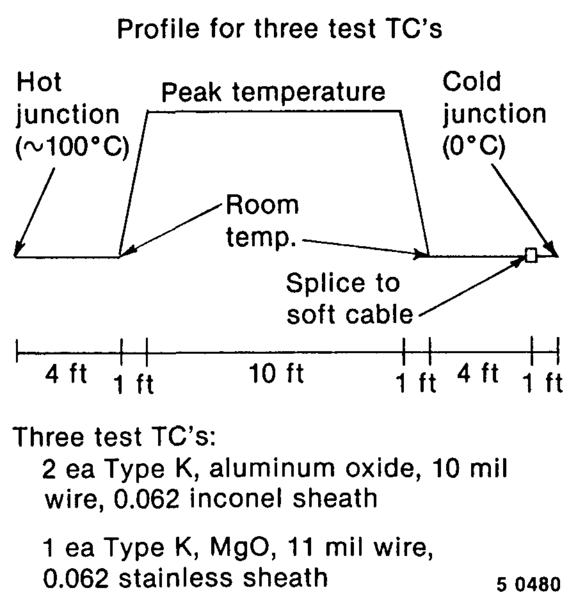

Figure 8. Temperature profile for three test TCs.

was a magnesium oxide insulated, 304 stainless steel sheathed, type K, 1.59 mm (0.0625 in.) o.d. thermocouple.

Since the objective of this test was to measure noise caused by high temperature shunting effects, the test was conducted in a manner to minimize background noise. Heater circuits, particularly those that are controlled by silicon controlled rectifiers (SCR) tend to generate considerable noise. To eliminate noise caused by the heaters, data were recorded with the heaters turned off. The sequence for conducting the test was to: (a) heat the furnace to 1271°C with the heaters, (b) stabilize the temperature, (c) turn on the recording equipment, (d) turn off the heaters, and (e) record the data. Data were gathered until the temperature decreased to about 900°C, since high temperature shunting errors did not occur below this temperature.

Data were recorded with three different devices: (a) normal dc thermocouple output was recorded on a strip chart recorder, (b) noise spectra from a spectrum analyzer were recorded on cassette magnetic tape, and (c) both normal dc output and noise signal were recorded on magnetic tape. This arrangement proved to be quite useful since it provided an indication of both shunting effects and noise levels during the test. By utilizing the on-line spectrum analyzer, test conduct could be altered, or unwanted noise could be eliminated during the test; and thus the likelihood of obtaining usable test results was maximized. Figure 9 shows how the thermocouples, amplifiers and recording equipment were connected. Note that two different types of amplifiers were used. The Neff amplifier provided a known gain to both the dc and the ac signals. The Princeton Applied Research (PAR) amplifiers provided the capability to separate the ac signal from the dc signal and further amplify the ac signal. This arrangement resulted in an output that was composed of both the ac and dc components and an output that was composed only of the ac component. This, then, permitted recording the magnitude of the temperature as well as the noise component of the temperature.

Analyses of the test data showed that significant shunting did occur at temperatures above 900°C but

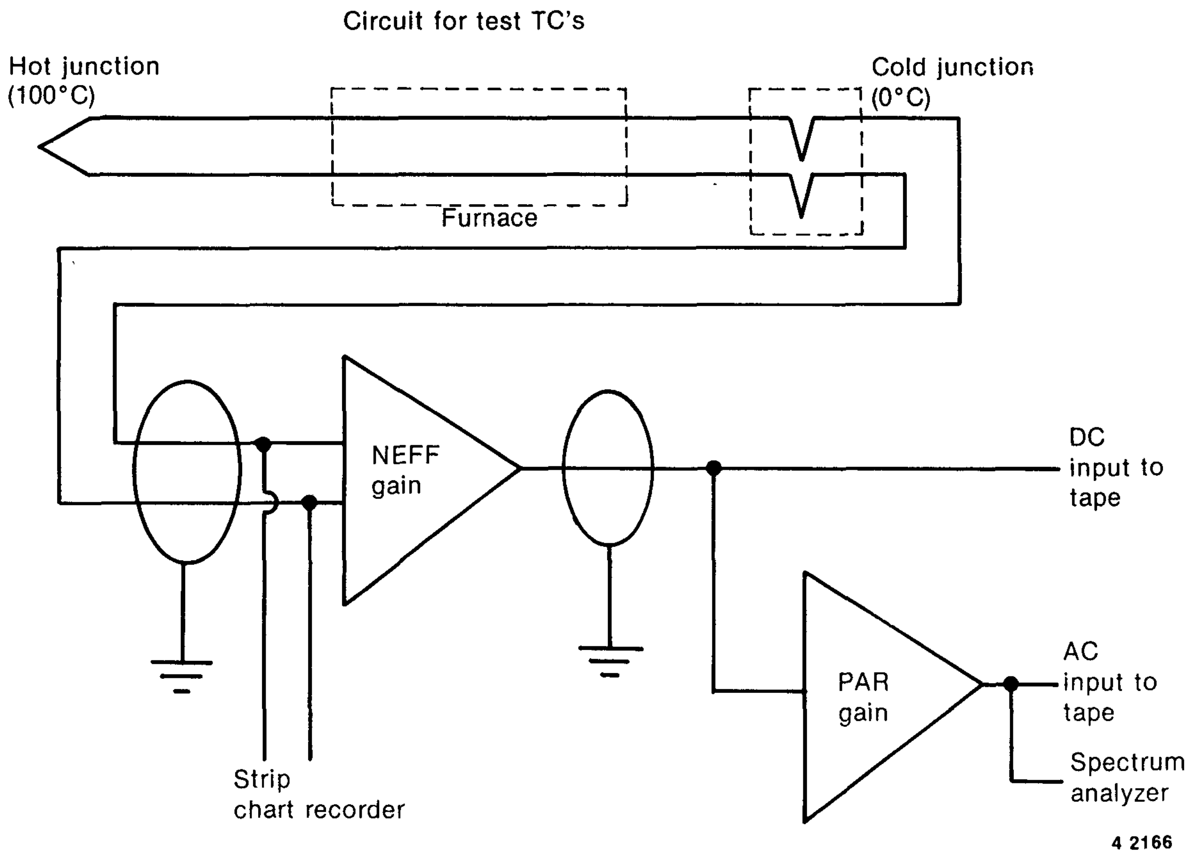

Figure 9. Circuit for test TCs.

no measurable noise was recorded that was attributable to high temperature shunting. Shunting effects varied in magnitude from 0°C at 900°C to a maximum of 800°C at 1271°C. Shunting in the magnesium oxide insulated, stainless steel sheathed thermocouple began at a higher temperature than it did for the aluminum oxide insulated, Inconel sheathed thermocouple. However shunting increased faster and became greater at high temperature for the magnesium insulated, stainless steel sheathed thermocouple. Figure 10 shows the shunting errors as a function of the peak temperature. The recorded noise levels were very small and did not change as temperature varied between 900 and 1271°C. Initial analyses of the noise showed that the magnitude of the spectrum decreased rapidly with increasing frequency and became insignificant above 400 Hz. Therefore, the final analysis of the noise was performed at frequencies below 400 Hz. The results of these analyses for both types of thermocouples are shown in Figures 11 and 12. Note that the spectrum for each temperature level has been shifted by 10 dB to avoid having the spectra all overlay each other. Note that the identifiable noise peaks are multiples of 60 Hz and are not related to performance of the thermocouples.

The conclusion reached from these tests is that while significant high temperature errors are produced for the temperature profile of Figure 8, no detectable noise is generated as a result of high temperature shunting. In addition, noise analysis is not expected to detect high temperature shunting in a commercial nuclear reactor during accident conditions since the tested profile was more conducive to producing shunting errors than that which is predicted for a severe accident.

Impedance Measurements. Impedance measurements can be used to provide credibility checks on TC temperature outputs. One simple check is to compare dc resistance with TC voltage outputs. They will correlate well during normal reactor operation since higher voltages are accompanied by higher resistances in a predictable manner. During credible accident sequences, the correlation between higher temperature and higher resistance will be valid until extreme temperatures are

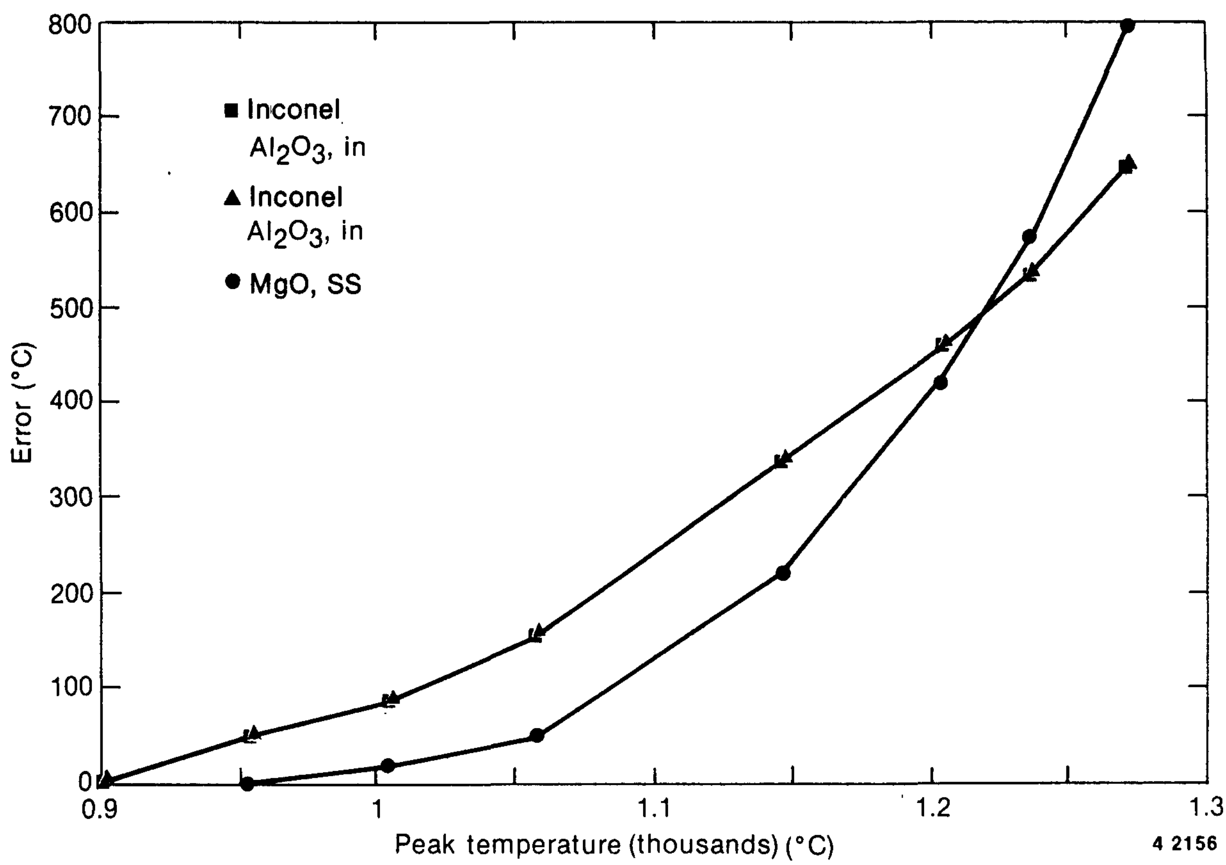

Figure 10. Shunting errors, Idaho Laboratory Facility Tests.

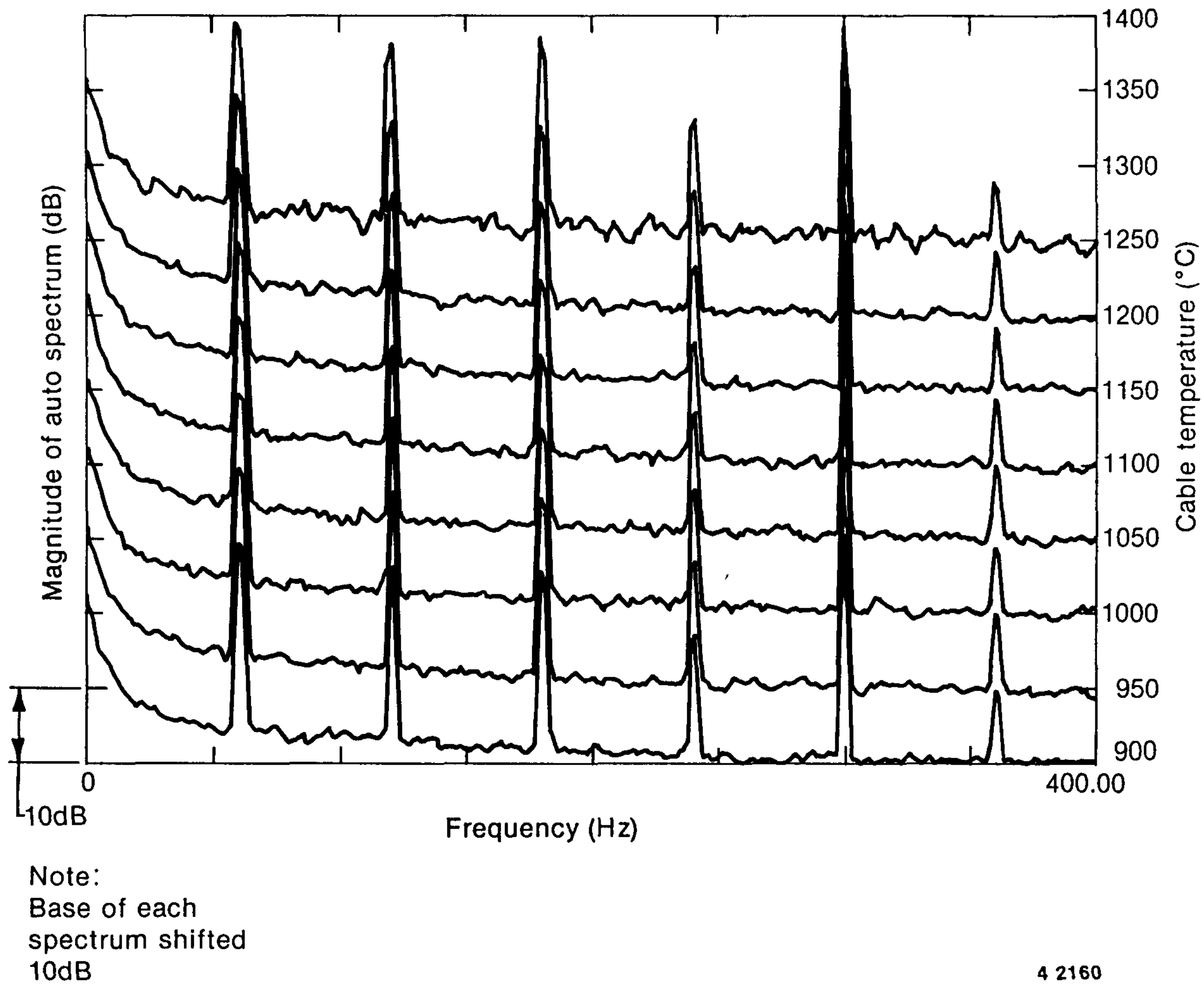

Figure 11. Noise analysis, cooldown—Al_2O_3, Inconel—composite plot.

reached. Extreme temperatures, in this context, are temperatures in excess of 1000°C. When a TC cable is subjected to temperatures such as these throughout much of the core, CET readings will not accurately reflect the core exit temperature.

There are two useful diagnostic tests based on impedance measurements that can help validate TC measurements when extreme temperatures are suspected in the core. The first diagnostic test uses the dc impedance (resistance). If the cable resistance begins to decrease with increasing indicated temperature, reduced insulation resistance such as occurs at extreme temperatures is indicated. This behavior is a signal that the TC output is in error and in nearly all cases the reading will be too high. Therefore, TC readings should be interpreted as an upper limit of the actual core exit temperature. This diagnostic is also valid for ac impedance when excitation frequencies are significantly below the resonant frequency of the TC circuit. A second diagnostic test uses the magnitude of impedance at the resonance frequency. This resonance typically occurs at a high frequency (∿3 MHz) and the impedance monotonically decreases with temperature. This measurement can be used as a double check of dc impedance, which is not a single valued function of temperature; that is, a given value of impedance does not correspond to a single value of temperature. By utilizing the impedance at resonance and the indicated temperature, an estimate of the peak temperature can be made for assumed temperature profiles. This has the potential to provide additional information to the operating crew concerning the status of the core.

Shorts and open circuits can be detected in most cases by comparing TC cable resistance with nominal values.

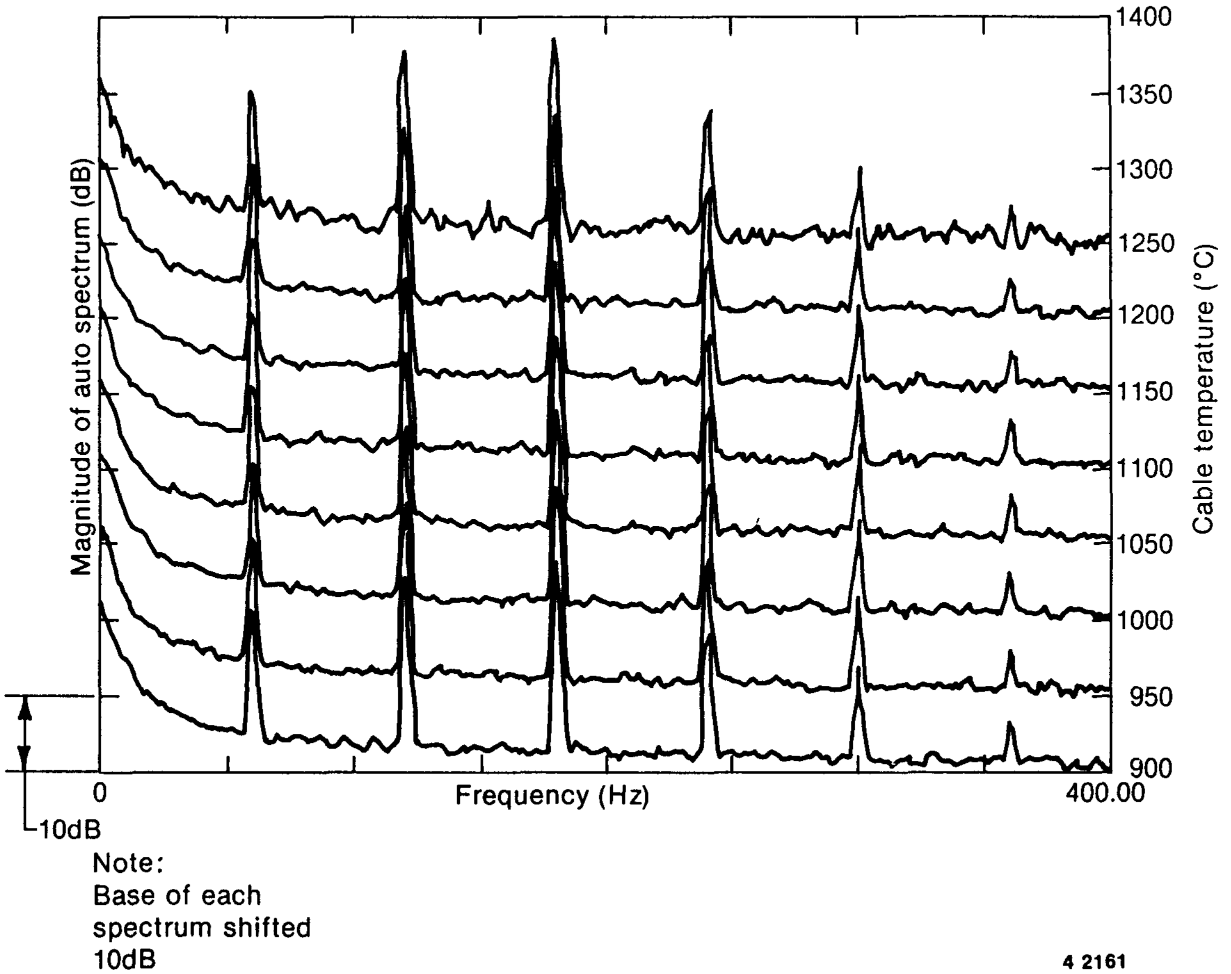

Figure 12. Noise analysis, cooldown—M_gO,SS—composite plot.

The following sections of the report will elaborate on the experimental and theoretical basis for using impedance measurements for TC data validation.

Modeling TC Impedance Behavior. A model of TC electrical behavior was developed in order to rapidly and cheaply explore the effect of various temperature profiles on TC cable. The main results from the modeling study were:

- DC resistance of a TC cable increases with increasing temperature until about 1000°C. After this the resistance decreases and TC measurement errors increase quickly. See Figure 13.

- A 3.56 m (12′) section of TC cable (about the height of a reactor core) will exhibit an impedance resonance between 1 and 3 MHz at reactor operating temperatures. The impedance at this resonant frequency decreases with increasing temperature for all temperatures. See Figure 14.

- For the severe accident scenario examined in this report, the roll off in dc resistance shown in Figure 13 was not observed. The probable explanation for this was that not enough of the TC cable became extremely hot in the scenario studied. Most of the cable would have to be heated to over 1000°C for the roll off to be observed.

The mathematical details of the TC model are given in Appendix B along with the temperature dependence of the physical properties used in the model.

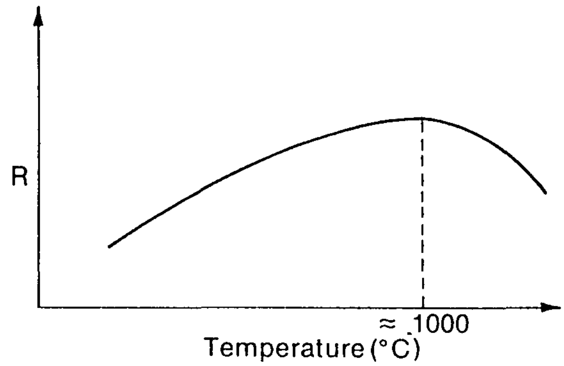

Figure 13. Resistance vs. temperature.

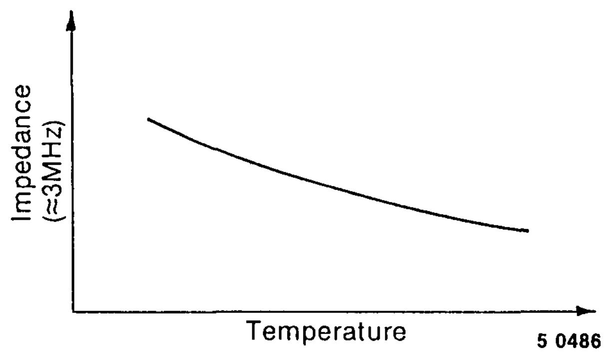

Figure 14. Impedance at resonance vs. temperature.

Calculated results for a station blackout transient were used to test the model with a predicted temperature profile.[21] A calculated temperature profile of the coolant in the core region during core uncovery is shown in Figure 15. As can be seen from the figure, most of the TC cable would experience temperatures below 1000°C and small shunting errors would be expected. This was confirmed by the model. For the profile of Figure 15, the TC model predicted temperature measurement errors of about +30°C. This is in contrast with the large errors calculated for other assumed profiles and confirms that high temperature caused errors are temperature and profile dependent.

Experimental Verification of Model. A series of oven experiments were run to verify the predictions of the TC model. Two series of experiments were run. The first was on a 3.53-m section of type K thermocouple cable typical of that used in the Three Mile Island Nuclear Power Plants. Impedance measurements were made at frequencies between dc and 10 MHz and temperatures between 22 and 1110°C. Comparisons between model predicted impedance and experimental results are shown in Figures 16 and 17. The comparison between model prediction and experiment is very good considering the wide variability in TC cable characteristics that result from the way they are manufactured.

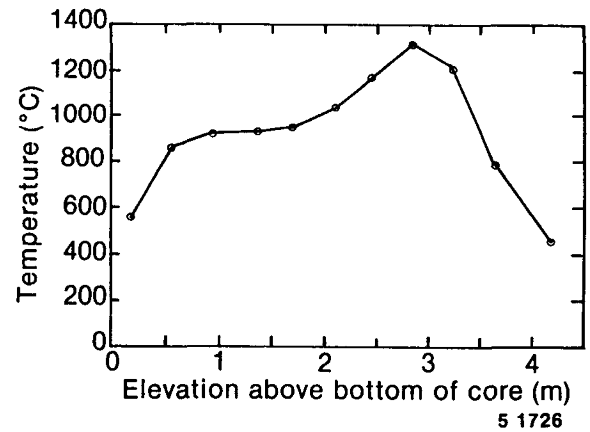

Figure 15. Temperature profile late into station blackout.

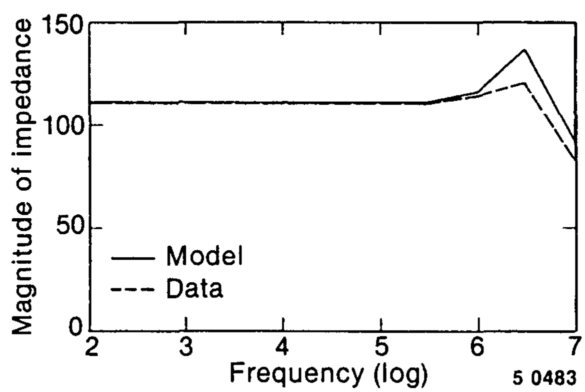

Figure 16. 300°C comparison of model and experiment.

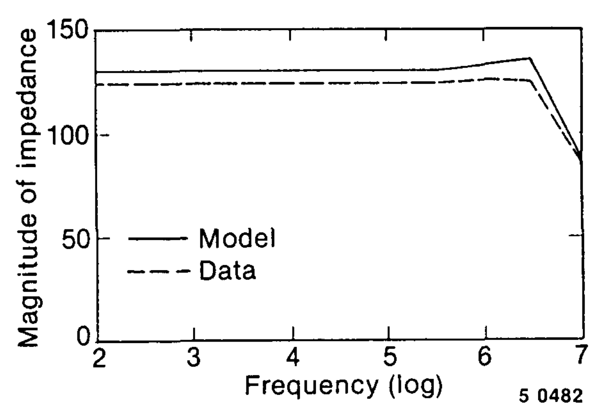

Figure 17. 600°C comparison of model and experiment.

A second series of experiments focused on TC measurement errors. A 6.1 m (20-ft) section of magnesium oxide insulated stainless steel sheathed, type K cable was tested, with the center 3.56 m (12 ft) heated in an oven. One end of the TC was placed in boiling water and at the other end the output voltage was measured. A comparison of model predicted temperature errors and experimental errors is given in Table 3. Significant TC errors begin at about 1000°C and they are on the high side, which is conservative for CETs. The model and experiment agree on the temperature at which temperature errors begin to appear. However, the magnitude of the errors is considerably different; the errors are underestimated by the model. This is what we expected, since the model used ideal material properties that cannot be attained in actual manufacturing. The model should accurately predict errors if the material properties, as manufactured, were utilized.

Statistical and Redundancy Analysis. Statistical techniques can be used for analysis to evaluate performance of'CETs. These techniques do not only use the performance characteristics of the thermocouple but also base the "failed" or "operating correctly" decision on thermal hydraulic characteristics.

Thermally all CETs basically read the same, i.e., within 100°F. This is true regardless of whether the system is subcooled, saturated, or superheated. This characteristic has been demonstrated in various test facilities such as LOFT. Therefore, one can use this characteristic to help identify failure of CETs.

Description of Techniques. The technique essentially consists of three parts: (a) range check, (b) noise check, and (c) normal distribution check using direct redundancy. The results of these checks will identify CETs as being acceptable, failed, or suspect. The following describes these three parts. A detailed description of these methods is given in a report by Brower et al.[22]

Range Check. The range check evaluates the CET to determine two things:

(1) Whether the CET output is within the valid measurement range.

(2) Whether noise clipping near the range limits is sufficient to influence the smoothed value significantly. Figure 18 illustrates the effect of clipping on the signal here considered as the mean value of the signal.

Table 3. Model predicted errors and experimental errors

Temperature (°C)	Model Prediction of Errors (°C)	Measurement Error (°C)
0 - 900	0	0
953	1	0
1804	5	19
1057	15	49
1146	71	221
1204	171	422
1236	255	575
1271	375	794

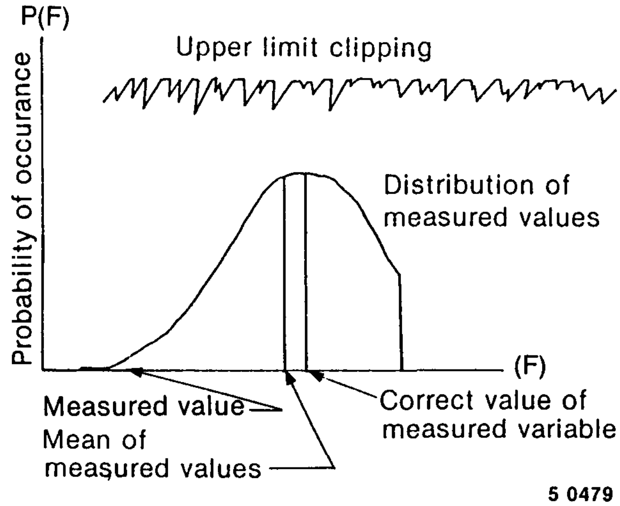

Figure 18. The effect of signal clipping.

To make these evaluations, the range check uses a smoothed time series data stream, {F}, and a skewness data stream, {S} where skewness is the third moment of a statistical analysis and is an indication of whether the data are normally distributed about a mean value.

Effectively, there exists an uncertainty band just inside each limit of the valid measurement range within which the effects of noise clipping should be evaluated. Figure 19 illustrates the location of these bands with respect to the valid measurement range. If the measured value is outside of the valid measurement range, F1 to F2, it is unacceptable. If it is in the range between the uncertainty bands, f1 to f2, it is acceptable. However, if it is inside one of the uncertainty bands it is acceptable only if the possible noise clipping has not introduced significant skewness, {S} in the noise about the smoothed signal estimate.

Noise Check. The second check is a noise check. This check consists of calculating the standard deviation of individual CETs and comparing it against the known systematic error and random noise (which is a weak function of the mean). If the standard deviation exceeds the limits determined from an analysis of systematic error and random noise, then the thermocouple is identified as anomalous. If the standard deviation is 0, then the CET is flagged as failed. Figure 20 shows the acceptable range of standard deviation (σ) as well as the upper (σ_h) and lower (σ_L) deviation.

Normal Distribution Check. After the above checks are complete and pass the respective tests, the signals are then subjected to statistical checks. The initial step is to calculate the average and standard deviation (σ) for all the CETs. If all the CETs are operational, they will read within ± 100°F (est.) of each other. If one has failed, it will read much

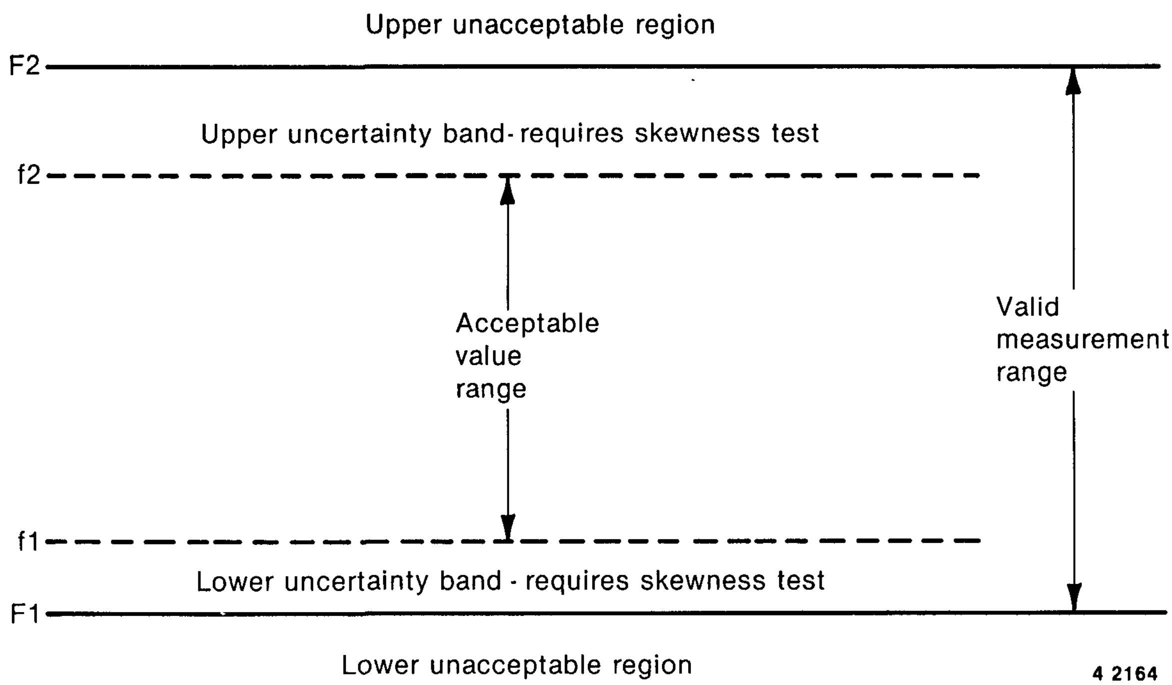

Figure 19. Location of uncertainty bands with respect to the valid measurement range.

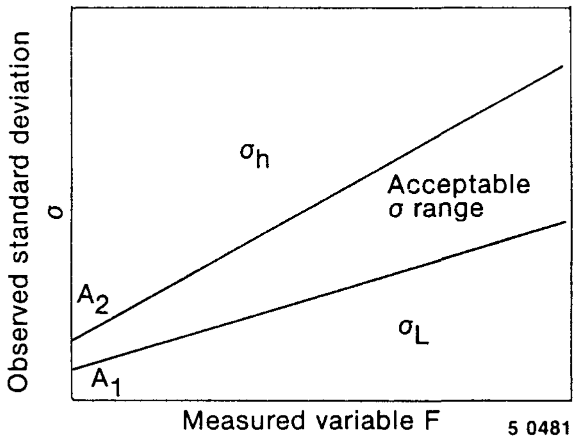

Figure 20. Acceptable range of standard deviation (σ).

higher or lower than the average of all TCs. This CET is then flagged as failed. Once it is failed it is not used in subsequent sample statistics again. If a CET is reading greater than or less than 2 σ from the average, this CET would be flagged as suspect.

Demonstrated Uses of Statistical and Redundancy Analysis. The Statistical and Redundancy Analysis (including range, noise, and distribution checks) are demonstrably useful in qualifying thermocouple data. These techniques have been utilized for the off-line qualification of transient thermocouple data at various test facilities at the INEL.[a] In addition, these techniques were used, with excellent results, for the performance of an on-line qualification of transient thermocouple data at the LOFT facility.[23]

Integrated Approach. Three techniques for on-line signal validation of core exit thermocouples have been discussed: (a) noise analysis, (b) impedance measurements, and (c) redundancy and statistical analysis. Noise analysis does not appear to be able to detect the existence of high temperature caused shunting errors. Impedance measurements are able to detect significant high temperature caused shunting errors as well as other circuit caused errors. However, neither of these techniques would detect amplifier and recording problems. While redundancy and statistical analysis are sensitive to nearly all sources of error, this method could lead to misjudgment as to which are the "good" and "bad" thermocouples. This misjudgment could occur if a majority of the CET were affected by high temperature at the same time and the bad thermocouples outnumbered the good ones.

a. LOFT, PBF, and Semiscale.

Since no one technique does an all inclusive job of on-line signal validation, it is advantageous to combine two or more methods to utilize the strengths of each. In this way, we obtain an overall validation that is superior to that which is obtainable by any one method. Figure 21 shows a block diagram that conceptually accomplishes this goal. The philosophy is that all thermocouples would be examined with respect to impedance in order to detect and identify those that were suffering from circuit related problems: open and short circuits, high temperature shunting, and melted thermocouples (particularly useful as a postaccident check).

Thermocouples that successfully passed the impedance measurements would be subjected to redundancy and statistical analysis for further signal validation. Redundancy and statistical analysis would determine: (a) if all measurements were on scale, (b) if redundant measurements agreed within their uncertainty, and (c) if all measurement were statistically well behaved. Measurements failing either the impedance measurements or the statistical and redundancy analysis would be considered unreliable and would be clearly identified as such. Only those measurements that passed both the impedance and the redundancy and statistical analysis would be identified as reliable for use in accident management. Specific details of impedance measurements and statistical and redundancy analysis are discussed in earlier sections.

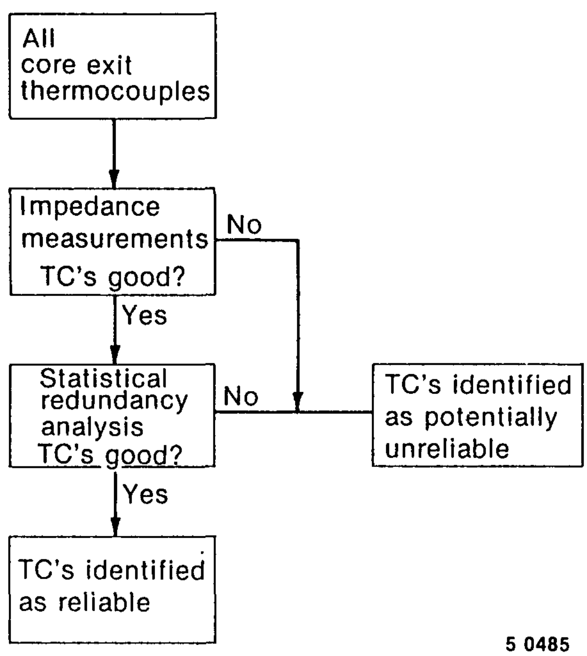

Figure 21. Integrated approach.

RECOMMENDATIONS FOR FURTHER INVESTIGATIONS PRIOR TO APPLICATION OF SIGNAL VALIDATION TO CORE EXIT THERMOCOUPLES

It is believed that the techniques presented in the section on Integrated Approach have the potential to provide satisfactory on-line signal validation for core exit thermocouples during severe accident situations. However, there are some areas that should be pursued further even though they were not included in this report. Some of these are:

- The total effects of impedance changes, as high temperature shunting becomes significant, should be predicted taking into consideration the total length of cable in the facility of interest. Only the length of cable in the core was considered in this report. Consideration should be given to the change in impedance as a percentage of the total impedance. For this technique to be successfully applied, the change in impedance that is to be detected must be measurable (using readily available equipment) and must not be so small that it cannot be reliably detected.

- The predicted temperature profile for the particular accidents and facility must be considered. Since high temperature errors are both temperature and profile dependent, it is recommended that errors be predicted in order to determine if they are expected to be of sufficient magnitude to be significant.

- Determine what relationship should exist, between the core exit thermocouples during accident situations, so that a criteria for redundancy analysis can be provided. This could be as simple as a logical grouping of thermocouples, or as complicated as attempting to predict, through analysis, the profile of the temperature at the plane of the core exit thermocouples.

- The potential to provide the operating crew with additional information concerning core temperature should be determined. It appears that a relationship exists between impedance at resonance and maximum thermocouple cable temperature for specified temperature profiles. However, utilizing this relationship depends on being able to predict or estimate the temperature profile and on being able to measure the change in impedance at resonance when long thermocouple cables are used. Both of these considerations should be pursued further.

APPLICATION TO OTHER MEASUREMENTS

There are other situations, apart from the testing of CETs during severe accident situations, when data users are being confronted with confusing and/or contradictory information and may benefit from on-line signal validation. While the specific requirements and the resulting techniques might be different than those for core exit thermocouples, the concept of signal validation and the process utilized to choose a technique would be similar. For this reason the concepts presented in this report are applicable to measurements in general.

While some of the specific signal validation techniques considered for core exit thermocouples would apply to other measurement systems, it is the process of choosing that is most applicable. The process presented in this report includes the following steps:

1. Identification of sources of errors for the measurement system under consideration
2. Evaluation and quantification of errors to identify those that are most significant to the measurement
3. Specification of requirements that must be met by signal validation techniques in order for the techniques to provide the information needed by the user of the data
4. Identification of possible signal validation techniques
5. Choosing those techniques that most fully meet the requirements and then performing more detailed engineering studies prior to applying them.

While it may be tempting to proceed directly to step 5 in the belief that enough is already known about signal validation techniques and their application to the measurements of concern, it is risky to do so. If a detailed understanding of which sources of errors are significant and what is required of a signal validation technique is not obtained, it is very likely that the technique implemented will either be much more complicated and costly than necessary, or will miss some crucial characteristic of the signal and be effectively useless. For example, if noise analysis was implemented alone as a signal validation technique for core exit thermocouples (based on previous experience with thermocouples being noisy as they failed) the results would not meet the needs and dissatisfaction would certainly follow. Therefore, it is recommended that the process presented here be followed and that steps not be skipped. Some steps may require only a small effort in order to provide the needed information, but obtaining information is important.

CONCLUSIONS

Signal validation techniques that may be suitable for core exit thermocouples in a nuclear reactor facility have been investigated. These techniques will detect the onset of high temperature caused errors that may not be obvious to the users of the data. Since indicated temperatures of CETs are used in decision making during an accident, this situation may lead to wrong decisions by the operating crew who are trying to take corrective action. Conclusions and recommendations have been reached based on technical, economic, and practical factors in respect to applying signal validation to an existing nuclear facility. These are:

- On-line signal validation of core exit thermocouples is feasible during steady state, accident and postaccident conditions. In fact, for signal validation to be most beneficial to an operating facility, it should be applicable to all three conditions.

- A combination of impedance measurements along with redundancy and statistical analysis is recommended. This combination of methods takes advantage of the strengths of each and at the same time tends to compensate for weaknesses that may exist for individual techniques.

- While the use of ac excitation is recommended to allow impedance to be measured without interfering with temperature monitoring, it does not result in more usable signal validation information than does dc excitation.

- Additional investigation into these signal validation techniques for CET should be performed prior to implementation. Areas of concern are: (a) change in impedance with respect to total impedance, (b) predicted temperature profile within the core during a severe accident, and (c) predicted relationship of core exit thermocouples to each other during a severe accident. Results of these investigations bear directly upon the ability to successfully implement the signal validation techniques.

- Techniques discussed in this report are applicable to situations that need signal validation for other measurement systems. Particularly applicable is the process for selecting a signal validation technique which defines the significant errors and requirements, and identifies potential techniques.

- A mathematical model of the measurement is a useful tool for evaluating signal validation techniques quickly and economically.

- Prior to implementing a signal validation technique, high temperature errors should be predicted considering the facility and the accident of interest. Not all facilities, nor all accident situations will result in significant high temperature caused errors.

- Investigation into the possibility of providing the operating crew with additional information concerning core temperature by utilizing impedance measurements should be performed.

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APPENDIX A

CANDIDATE TECHNIQUES FOR SIGNAL VALIDATION

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Techniques Considered for Signal Validation

Time Domain Noise Analysis. This method involves observing the noise in a TC signal for a period of time and correlating changes in the magnitude of the root mean square (RMS) value of the noise with physical changes in the TC. Observations of the LOFT fuel cladding TCs have led some people to suspect that noise level increases as shunting and virtual junction effects become significant. Therefore, the likelihood of success is considered to be medium. Since the technique of utilizing time domain noise analysis as an input to data qualification has been developed and applied to LOFT data, the cost of development should be low.

Frequency Domain Noise Analysis. This technique is similar to time domain noise analysis, but rather than measuring only the RMS magnitude, the frequency and phase relationship of each frequency component of the noise is measured. Usually longer periods of data collection are required for frequency domain than for time domain analysis. Because of the similarity in the two techniques, the likelihood of success is considered to be the same, medium. However, this technique is more complicated than time domain noise analysis and, therefore, the cost for development is judged to be medium.

Time Domain Reflectometry (TDR). TDR involves exciting the TC with a fast rise time pulse (composed of high frequencies) and observing the reflected pulse. Typical TC cabling would be composed of about 106.7 m (350 ft) of extension cable and about 39.6 m (130 ft) of metal sheathed, mineral oxide insulated cable. The metal sheathed cable has high loss characteristics at high frequencies, which means that the velocity of propagation and attenuation become strong functions of frequency. This results in broadening or smearing of the pulses, which makes them difficult to detect. Also, the ability to relate results of a TDR examination to the onset of high temperature caused ambiguities is not known and considerable testing would be required. Therefore, the likelihood of success is considered low, while the cost to develop is high.

Response to Excitation. Since the problem with TDR is the high frequencies involved and the high loss thermocouple cable, the possibility exists for useful information to be obtained by utilizing other excitations; particularly, a low frequency excitation. Considerable testing would have to be done to optimize the excitation signal and to interpret the results; therefore, the cost would be high. The probability of success is higher than with TDR; the probability of success is judged to be medium.

Measure Loop Impedance, Etc. It is known that as thermocouple temperature increases, conductor resistivity increases, insulation resistance decreases, and capacitance increases. R. L. Shepard, R. F. Hyland, J. M. Googe, and J. R. McDearman have reported[1] that the loop resistance of a 1.57-mm o.d., tantalum-sheathed, W-3% Re/W-26% Re, thoria-insulated thermocouple would reach a peak and then decrease as shunting errors became significant. It is suspected that this effect may be more pronounced if ac impedance was measured rather than dc resistance. In addition, other characteristics such as the dielectric constant, insulation resistance and the circuit time constant can be determined and may correlate to high temperature errors. The probability of success is judged to be medium and cost to develop is medium.

Comparison to Other TCs and Other Measurements. Data from measurement channels can be validated by comparing redundant measurements, similar measurements, and other measurements that are related by laws of physics or by facility configuration. This technique has been successfully applied to validation of test data from LOFT experiments. Some concerns that arise when applying the method to accident and post accident instrumentation are:

- The need to perform the validation online. This is probably a minor concern since computers can readily make the comparison and indicate the results.

- If a majority of the CET were affected by high temperature at the same time, the technique could label the failed TCs as good and the good TCs as failed since the good TCs would be the exceptions. This situation is not believed to be likely, but it is an inherent weakness of the approach.

The probability of success is medium and cost to implement is medium. If this technique is combined with measurement of loop impedance, the probability of success is increased since further indication of a failed TC would be provided.

Compare to Past Data. This technique involves obtaining a data base of wire to wire, and wire to sheath, voltages and resistances at known operating and shutdown temperatures. Identical measurements would be taken postaccident and compared to the data base. If corresponding measurements did not agree, the TC would be labeled as failed or at least suspect. This technique has been proposed by A. C. Williams and Ned Wilde.[2] Since this method only provides a preaccident data base and is limited by not being able to address reversible errors, it is valid only for pre- and postaccident conditions. While the probability for success is high and cost is low, this method is not applicable during an accident, and was not given further consideration.

Use TC Wires as Tuned Legs of an Oscillator. EG&G personnel have considered this technique as a method to determine the health of instrumentation cables at TMI. With the TC wires connected as tuned legs of an oscillator, the frequency of oscillation is a function of cable length and cable characteristics. Some of the problems to be considered are:

- Cable length must be well known
- The temperature affected zone is small compared to the total cable length and the net change may be small
- The metal sheathed cable has high loss characteristics at the high frequencies that are typically used
- The correlation to TC errors is unknown.

The likelihood of success was judged to be low and the cost to develop is high due to the large amount of testing that would be required.

Use TC Wires as Ultrasonic Conductors. This technique would be similar to an ultrasonic thermometer where an ultrasonic signal would be correlated to TC error. Since a metal sheathed cable has wires in constant intimate contact with the insulator, essentially no ultrasonic signal will be transmitted along the TC wires. Therefore, this technique has very low probability of success and would entail very high costs to develop.

Response to Energy Input-Thermal Time Constant. Loop current step response transient testing has been developed and applied successfully to RTDs. In addition, the technique has been demonstrated to work for thermocouples, but apparently has not been applied on a commercial basis. Since the technique involves monitoring the transient cooldown response of a thermocouple after a heating current has been removed, the thermocouple must be in a steady state environment in order not to alter the induced transient. Therefore, this technique is considered to be valid for only pre- and postaccident conditions and was evaluated on that basis. Because the method has had considerable development and some demonstrated success, the likelihood of success is judged to be high and cost to develop is considered to be medium.

Utilize Peltier Effect. In 1834 Jean Charles Athanase Peltier, a French physicist, discovered peculiar effects when he introduced small, external electric currents in Seebeck's bismuth-antimony thermocouple. His experiments demonstrated that when a small electric current is passed across the junction of two dissimilar metals in one direction, the junction is cooled (i.e., it acts as a heat sink) and thus absorbs heat from its surroundings. When the direction of the current is reversed, the junction is heated (i.e., it acts as a heat source) and thus releases heat to its surroundings. To utilize this effect, enough heating or cooling must be generated to produce a usable output. Since the TCs are grounded and have very good association with the surrounding medium, considerable heat transfer would be required, particularly when the TCs are surrounded by water. This would require the application of a large electric current to generate the required amount of heat transfer and would likely result in considerable heating of the wires through power loss in the wires. This, combined with the fact that the medium can be water, steam, or an unknown combination, makes the probability of success low. Considerable testing would be required to verify the method and, therefore, costs would be high.

Excite One Conductor/Sheath Combination—Return Signal Propagated in the Other Conductor. This technique utilizes the fact that the velocity of propagation of an electrical wave is a function of the dielectric constant. The delay of the return signal would be a function of the dielectric constant which is a function of the cable temperature. However, in a metal sheathed thermocouple cable, capacitance is high, series resistance is relatively high, and shunt resistance may be low. These characteristics would require the application of high frequencies for the usual assumptions concerning dielectric constant and velocity of propagation to be valid. Since the frequencies would be high and the losses would also be high, the probability of success is low. Considerable laboratory testing would be required and cost is expected to be high.

Redesign or New Installation. Items 13 through 18 of Table 2 are primarily related to a redesign of either the facility or the thermocouple. Since one of the mandatory requirements of this study requires use of existing instruments, these items were not given further consideration. However, some of these techniques may be very useful if a new facility was being designed and, in that case, should probably receive further consideration.

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APPENDIX B

MODEL OF THERMOCOUPLE ELECTRICAL BEHAVIOR

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The model implemented in this study of thermocouple electrical behavior uses concepts from transmission line theory. Transmission lines are similar to TCs in that they are made up of two wires separated by an insulating material and encased in a sheath. The electrical behavior of transmission lines and TCs can be analyzed by considering them to be a series of short lumped parameter segments that have discrete parameters of Inductance, Resistance, Capacitance (L, R, C). An additional feature of TCs is that they have voltage generated in segments subjected to temperature gradients. Figure B-1 shows an equivalent L, R, C circuit for a short segment of type K thermocouple. The equivalent circuit is made up of three wires, one each for the two TC wires and the sheath. Capacitive coupling and noise currents between the wires are included in the model.

The symbols in Figure B-1 are defined as follows:

> I_1 (i) and V_1 (i) are the current and voltages at the beginning of segment i in wire 1 of the thermocouple.
>
> C_s (i) and G_s (i) are the capacitance and conductance between the TC wires and the sheath of segment i.
>
> i_s (i) is the noise current between the TC wires and the sheath of segment i.
>
> C_p (i) and G_p (i) are the capacitance and conductance between wire 1 and wire 2 of segment i.
>
> ν_{s1} is the Seebeck voltage generated in wire 1 over the segment's length.
>
> R_1 (i) and L_1 (i) are the resistance and inductances of segment i of wire 1.
>
> The subscript 2 stands for wire 2 and the subscript o stands for the sheath.

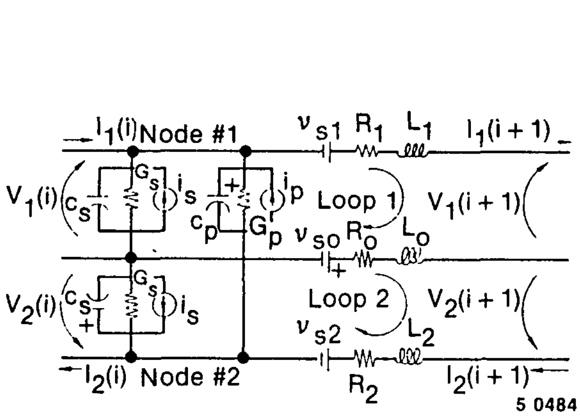

Figure B-1. An equivalent L, R, C circuit for a short segment of type K thermocouple.

When modeling TC behavior, segments should be small compared to the distance over which significant changes occur in the TC parameters and the wave length of electromagnetic waves propagating in the TC. Equations for the current flows and the voltages in each segment can be derived from Kirchoff's current and voltage laws.

Referring to Figure B-1, the voltage equation for loop 1 is:

$$[L_o(i) + L_1(i)]\,\dot{I}_1(i+1) - L_o(i)\,\dot{I}_2(i+1)$$
$$= V_1(i) - I_1(i+1)\,[R_o(i) + R_1(i)] + I_2(i+1)\,R_o(i) - V_1(i+1) + V_1(i) + \nu_{s1}(i) - \nu_{so}(i) \quad (1)$$

and the voltage equation for loop 2 is:

$$- L_o(i)\,\dot{I}_1(i+1) + [L_2(i) + L_o(i)]\,\dot{I}_2(i)$$
$$= - V_2(i) + I_1(i+1)\,R_o(i) - I_2(i+1)\,[R_o(i) + R_2(i)] + V_2(i+1) + \nu_{so}(i) - \nu_{s2}(i) \quad (2)$$

and the current equations for node 1 and 2 are respectively:

$$[C_p(i) + C_s(i)]\,\dot{V}_i(i) - C_p(i)\,\dot{V}_2(i)$$
$$= - [G_s(i) + G_p(i)]\,V_1(i)$$

$$+ G_p(i) V_2(i) + I_1(i)$$

$$- -I_1(i+1) + i_s(i) + i_p(i) \qquad (3)$$

$$-C_p(i) \dot{V}_1(i) + [C_s(i) + C_p(i)] \dot{V}_2(i)$$

$$= G_p(i) V_1(i) - [G_s(i)$$

$$+ G_p(i)] V_2(i) - I_2(i) + I_2(i+1)$$

$$+ i_s(i) - i_p(i) \qquad (4)$$

where $V_1(i)$ is the time derivative of voltage in wire 1 at element i. The voltages and current in thermocouple satisfy a set of equations like (1) through (4). This set of equations can be written in state space form as in Reference 1.

$$A\dot{x} = Bx + u \qquad (5)$$

where

$$x = \begin{bmatrix} V_1(1) \\ V_2(1) \\ I_1(1) \\ I_2(1) \\ . \\ . \\ . \\ . \\ I_1(n) \\ I_2(n) \end{bmatrix} \quad u = \begin{bmatrix} i_s(1) + i_p(1) \\ i_s(1) - i_p(1) \\ \kappa_{s1}(1) - \kappa_{so}(1) \\ \kappa_{so}(1) - \kappa_{s2}(1) \\ . \\ . \\ . \\ . \\ \kappa_{s1}(n) - \kappa_{so}(n) \\ \kappa_{so}(n) - \kappa_{s2}(n) \end{bmatrix} \qquad (6)$$

n is the number of elements used to model the thermocouple. A and B are 4n by 4n banded symmetric matrices. The upper left 4x4 submatrices of A and B are as shown in equation (7).

The state space Equation (5) can be solved for time response of currents and voltages in a TC using standard differential equation solvers.[2] For instance, the response of a thermocouple to rapid dielectric thermal relaxation can be determined using (5). This is done by setting i_s and i_p to large values for a short time and solving for the resulting currents and voltages. The TC response to a sudden change in temperature can be solved for by changing the temperature dependent parameters rapidly (e.g., Rs, Ls, κs, etc.).

An important use of the model is in determining the impedance of a thermocouple for various temperatures. The predicted impedances can be compared with measured impedances to aid in validating and/or correcting TC data during ICC incidents. The impedance is found by solving

$$j\omega Ax = Bx + u \qquad (8)$$

for the real and imaginary parts of $V_1(1)$ and $V_2(1)$, where j is the square root of -1, $\omega = 2\pi f$, and f is the frequency at which the impedance is evaluated. A, B, and u are functions of the selected temperature profile. A set of equations for the real part of x (Rex) and the imaginary part of x(Imx) are

$$[\omega A + B (\omega A)^{-1} B] \,\text{Imx} = -\text{Reu} - B(\omega A)^{-1} \text{Imu} \quad . \ (9)$$

$$\omega A\text{Rex} - B \,\text{Imx} = \text{Imu} \qquad (10)$$

These equations can be solved using standard linear equation solution techniques.[2]

The model described above has been implemented on the dual CYBER 176 system at the Idaho National Engineering Laboratory (INEL). The mathematical library routines in the IMSL[2]

$$\begin{bmatrix} C_p(1)+C_s(1) & -C_p(1) & o & o \\ -C_p(1) & C_p(1)+C_s(1) & o & o \\ o & o & L_o(1)+L_1(1) & -L_o(1) \\ o & o & -L_o(1) & L_o(I)+L_2(1) \end{bmatrix}$$

$$\begin{bmatrix} -[G_s(1)+G_p(1)] & +G_o(1) & -1 & o \\ +G_p(1) & -[G_s(1)+G_p(1)] & o & -1 \\ 1 & o & -[R_o(1)+R_1(1)] & R_o(1) \\ o & -1 & R_o(1) & -[R_o(1)+R_2(1)] \end{bmatrix} \qquad (7)$$

package are used to do much of the calculations. As the model is currently written, up to 400 elements can be used to model the thermocouple. The model calculates the impedance of a TC using a 400 elements in < 1 s of CPU time.

The data for the model were obtained from the literature on materials properties and calculations based on the geometry of the TC. For the type K thermocouple discussed in this report, the thermocouple wires were Chromel and Alumel, the sheath was Inconel and the dielectric was AL_2O_3. The resistivity (RHO) data used were

$$RHO(T) = EXP[49.6 - 4.92 \times 10^{-2} \times T + 1.63 \times 10^{-5} \times T^2]$$

for AL_2O_3 (References 3-5)

$$RHO(T) = 70.0 + 3.29 \times 10^{-2} \times T - 6.98 \times 10^{-6} \times T^2$$

for Chromel[6,7]

$$RHO(T) = 29.77 + 4.39 \times 10^{2} \times T - 1.29 \times 10^{-5} \times T^2$$

for Alumel[6,7]

$$RHO(T) = 101.77 + 2.13 \times 10^{-2} \times T - 6.92 \times 10^{-6} \times T^2$$

for Inconel[8]

where T is temperature in degrees centigrade.

The value for the relative dielectric constant of AL_2O_3 (Reference 9) was

$$\frac{\epsilon}{\epsilon_o} = 8.6$$

and the relative permittivity of all materials was set at 1. None of the materials in the TC studied were ferromagnetic. Given these data and the geometry of the TC, inductance, conductance, and capacitance per length of cable can be calculated.[10] The model assumed that the TC was of uniform cross section 63 mils in diameter with 11-mil wires and 7 mils of insulation between wires and 7 mils between wires and the sheath. Manufacturing variations in TCs will cause some differences with the data used in the model. This is probably the major source of model error.

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